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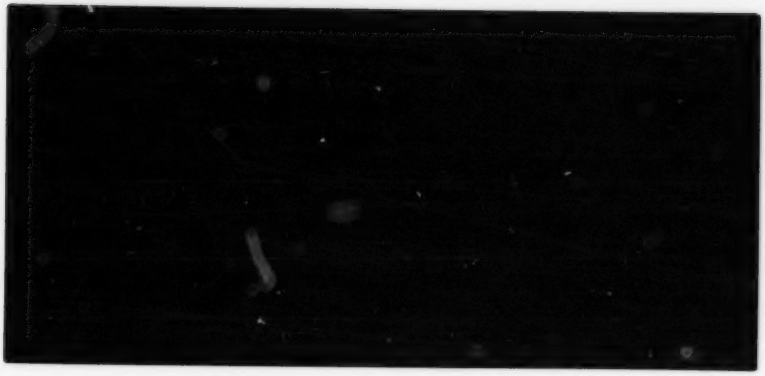

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Degradation of Environmental Capital and National Accounting Procedures

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Degradation of Environmental Capital and National Accounting Procedures

The findings of this paper are the personal responsibility of the author and, as such, have not been endorsed by the Members of the Economic Council of Canada.

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Foreword

This paper provides a rigorous mathematical/theoretical foundation for the conceptualization of the "natural environment" as a wastable capital stock. The treatment has important implications for the measurement of degradation (and enhancement) of environmental capital in relation to "adjusted" calculations of net national product and its corresponding growth rate. Since the treatment of this issue is mainly theoretical, the task of making the suggested measures "operational" remains to be done.

The paper is a first contribution to the Economic Council's planned project on Environmental Issues. The author of the paper, John M. Hartwick, is professor of economics at Queen's University in Kingston, Ontario.

Judith Maxwell
Chairman

Abstract

The capital theoretic approach to the environment as a wastable stock, a stock with a flow of abatement services, is explored in a simple Ricardo-like model involving wheat production and pollution production as an essential by-product. We then turn to how the national accounts are implicit in growth or capital theory models and how formulas emerge for accounting for the wasting of environmental capital (airsheds and watersheds) from "excessive" use.

Introduction

In accounting for the degradation of the environment in the national accounts, we follow a capital theoretic approach. Roughly speaking, the environment is treated as a renewable resource (see Dasgupta [1982] for a discussion of this approach). The environment (airsheds and watersheds) "evaporates" residuals or pollutants at a rate which depends on the size of the environment or on its quality as a stock yielding a physical flow of services. Different sizes of stock or environmental capital correspond to different amounts or volumes of flows of abatement services. The wasting or degradation of the environment corresponds to a diminution in the size of the environmental stock or capital. A ready measure of environmental stock size is the volume of pollutants suspended in the environment year by year. Stock size diminution then corresponds to a larger volume of residuals persisting in the environment. This capital theoretic approach shifts attention away from the traditional question in static analysis of how best to achieve target level x of pollution. However, in our framework the so-called target level is endogenously arrived at by the dynamic interaction of the pollution-generating "technology" and the "production" of abatement either by nature alone or by nature assisted by human intervention. We do observe a gap between shadow values of inputs inclusive of marginal pollution damage arising from their use and market prices for inputs. Thus within our model is the familiar gap to be filled by optimal taxes, but we gloss over this territory in order to focus attention on the correct expressions or formulas for valuing the wasting of environmental capital or stocks. It is a matter of arriving at correct formulas for calculating the economic depreciation of environmental capital arising from its degradation due to "overuse."

A merit of our approach is that it treats the accounting for the wasting or degradation of environmental capital the same as that of the wasting or degradation of exhaustible resource stocks and/or renewable resource stocks such as fish and forests [e.g., Hartwick, 1990]. Our formulas emerge from explicit capital theory or derive from growth models and are not presented simply as ad hoc insights.[1]

First we set out a simple economy-wide dynamic model involving "wheat" production with a pollutant as by-product. We analyse aspects of this model including the extension to a model with a human-engineered abatement sector. Then we turn to the derivation of formulas for economic depreciation of environmental capital or how to extend the national accounting procedures to incorporate diminution or degradation in stocks of environmental capital. We move from our simple Ricardian model with pollution to a quite general model which permits us to see how formulas for economic depreciation change as the way one treats pollution impinging on the economy changes.

Capital Theory and Pollution: A Basic Model

Suppose in a Ricardian world of a plot of land, worked by labourers available in infinite supply at subsistence wage w, the production of wheat also yields pollution. This pollution degrades the land for agricultural purposes and "evaporates" at a constant rate over time. How much labour should be applied to the land? The answer depends on how degraded the land is at any moment. Wheat production yields pollution and pollution degrades the land for wheat production. Thus we have an inherently dynamic model of "wheat" production. One solution would clearly be a steady state variant in which the pollution stock remained constant (as well as the labour force and output) while new pollution was matched by pollution "evaporation." Another solution could involve a cycle of increasing degradation of land, labour withdrawal, restoration of land fertility, increasing production and degradation, labour withdrawal, and so on. The cycle might repeat forever as in the Lotka-Volterra predator-prey model or it might converge to a steady state. Another possibility might be the "mining" of the land by letting pollution accumulate and the labour decline asymptotically into the indefinite future. Thus the simple extension of the simple Ricardian model to a world of pollution and dynamic abatement opens up a rich set of new scenarios to reflect on.

We set out the model, examine some of its properties and sketch the dynamics.

Given a fixed amount of land, wheat Q is produced from labour N and impeded by pollution stock R (residuals).

$$Q = f(N,R)$$

with

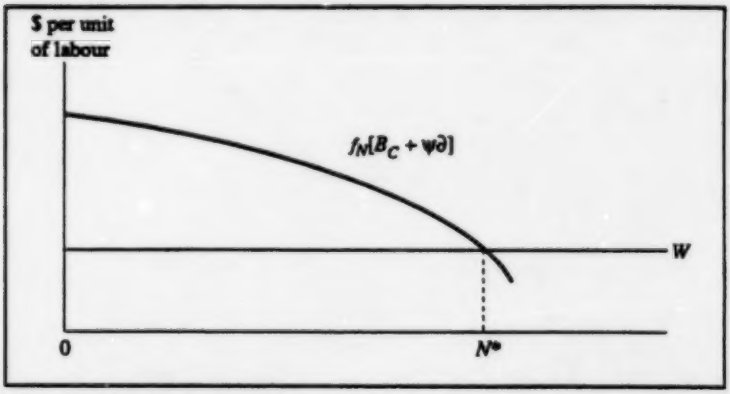
$$f_N > 0 \text{ and } f_{NN} < 0,\ f(0,R) = 0 \text{ and } f_R < 0,\ f_{RR} > 0 \text{ and } f(N,0) > 0. \qquad (1)$$

Labour is available in infinite supply at wage w. Given R at some positive level, an equilibrium would be reached as sketched in Chart 1.

A higher level of pollution stock R shrinks the value of the marginal product of labour scheduled in Chart 1, implying a lower steady state level of labour N^* employed. Observe that it is the value of the *net* marginal product of labour which equals the wage, that is, the marginal product net of the extra pollution at the margin generated by increased output Q. The optimal tax required to make the market price of labour w equal to the shadow value of labour is $-f_N \Psi \gamma$ where $\Psi < 0$. At the margin, a unit of labour not only produces output (wheat) worth B_C per unit but also "produces" pollution at level $-f_N \Psi \gamma$ per unit of labour. $B(C)$ is the aggregate consumer surplus associated with consumption C.

Chart 1

A Possible Steady State Solution Given a Constant Stock of Pollution with New Increments in Pollution Equal to the Amount Abated by Nature



NOTE N is labour in wheat production.

Natural abatement proceeds at $-\dot{R} = bR$ where b is the rate of exponential decay in the stock. We assume b positive and less than 1. Production generates new pollution $\dot{R}$ according to $\gamma f(N, R) = \dot{R}$ with $\gamma > 0$ and constant. The net change in the pollution stock is:

$$\dot{R} = -bR + \gamma f(N, R). \tag{2}$$

In a steady state $\dot{R} = 0$ or natural abatement $-bR$ equals new pollution increment $\gamma f(N, R)$. In a perpetual cycle R will oscillate between two values R_U^* and R_L^* and this will result in labour oscillating between two values N_L^* and N_U^*. Finally in a collapse mode, $\dot{R} > 0$ and R keeps rising as N declines into the indefinite future.

The landowner or planner maximizes $\int_0^\infty [B\,(C(t)) - wN\,(t)]\, e^{-\rho t}\, dt$, which is the present value of surplus (land rent plus consumer surplus) for a landowner.[2] $C(t)$ is the consumption of wheat and equals $f(N, R)$. We ignore replanting costs or annual investment in next period's seed. The equation of motion is equation (2). The current Hamiltonian value for this problem is:

$$H = B(f(N, R)) - wN + \psi[\gamma f(N, R) - bR]. \tag{3}$$

The canonical equations are:

$$\frac{\partial H}{\partial N} = 0 \rightarrow [B_C + \Psi\gamma]f_N = w; \tag{4}$$

$$-\frac{\partial H}{\partial R} = \dot{\Psi} - \Psi\rho \rightarrow -B_C f_R - \Psi\gamma f_R + b\Psi = \dot{\Psi} - \Psi\rho; \tag{5}$$

$$\frac{\partial H}{\partial \Psi} = \dot{R} \rightarrow \dot{R} = \gamma f(N, R) - bR. \tag{6}$$

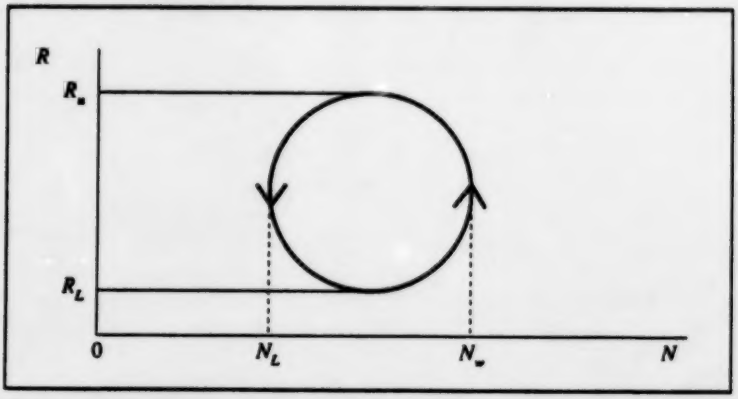
ψ will be negative in a steady state. It is the shadow price of pollution stock R. Thus $[B_C + \psi\gamma]$ is the net price of wheat, net of pollution induced by more output, and $[B_C + \psi\gamma]f_N$ is the net value of the marginal product of labour. If we solve for ψ in equation (4) and obtain

$$\dot{\Psi}\left[= \left\{\left(-f_N^2 \frac{\partial B_C}{\partial N} - wf_{NN}\right)/\gamma f_N^2\right\}\dot{N} + \left\{\left(-f_N^2 \frac{\partial B_C}{\partial R} - wf_{NR}\right)/\gamma f_N^2\right\}\dot{R}\right],$$

we can substitute in equation (5) and obtain a pair of simultaneous differential equations in R and N. The solution of this pair defines the dynamics of the model given initial value R_0 for the pollution stock. We recapitulate. The three possible dynamic scenarios are: (i) that the system converges to a steady state (R^*, N^*); (ii) that the system cycles perpetually around R_U, N_L, R_L, and N_U; or (iii) that the system collapses to $N(t) \rightarrow 0$ as $t \rightarrow \infty$. We sketch the cycle scenario[3] in Chart 2. (A steady state was set out in Chart 1.)

Chart 2

A Possible Perpetual Pollution Expansion-Contraction Cycle for the Simple Ricardian Model



In order to understand the model, we parameterized some selected functional forms and performed some comparative static exercises that perturbed the steady state N and R. We selected a production function for wheat of the form N^{α}/R^{β} and $U(C) = C^{.5}$. Our base case had $\alpha = .5$, $\beta = .001$, $\gamma = .1$, $\rho = .05$, $b = .5$, and $w = .1$. We observed:

W	$\uparrow$	$\rightarrow$	R	$\downarrow$,	N	$\downarrow$;
γ	$\uparrow$	$\rightarrow$	R	$\uparrow$,	N	$\downarrow$;
β	$\uparrow$	$\rightarrow$	R	$\uparrow$,	N	$\uparrow$;
b	$\uparrow$	$\rightarrow$	R	$\downarrow$,	N	$\uparrow$;
ρ	$\uparrow$	$\rightarrow$	R	$\downarrow$,	N	$\uparrow$.

Note that when output generates more pollution ($\gamma \uparrow$), the steady state ends up with a higher pollution stock and lower numbers of workers employed. When the pollution stock impinges more adversely on production ($\beta \uparrow$), the steady state level of the pollution stock rises and the number of workers increases, though output Q declines. When nature is a more powerful abater ($b \uparrow$), the steady state pollution stock is lower and more labour is employed. From a policy standpoint, one would like to lower γ, the amount of pollution yielded per unit of wheat produced. A reduction in γ lowers the steady state pollution stock and raises the amount of labour employed. The model immediately below makes γ a choice variable but lower values of γ cost more to put in place or install than higher values.

The Polluted Ricardian World with Human-Engineered Abatement

We introduce human-engineered abatement by assuming that γ can be set at a smaller level if γ is invested in. That is, output will yield less new pollution if γ is set at a smaller value. We simply introduce "investment" $g(\gamma)$ in the accounting relation $Q = C + g(\gamma)$, with $g_{\gamma} < 0$ or a smaller γ more costly to maintain. The new objective function is $\int_0^{\infty} \left[B\left[f(N,R) - g(\gamma) \right] - wN \right] e^{-\rho t} dt$

and the equation of motion is unchanged. Now there are two control variables, namely N and γ, and one state variable, namely R. This implies three simultaneous differential equations in N, γ, and R defining the dynamics of the system.

The current Hamiltonian value is now:

$$H = B[f(N,R) - g(\gamma)] - wN + \eta[\gamma f(N,R) - bR], \tag{7}$$

where η is the co-state variable or current shadow price on R. The canonical equations are:

$$\frac{\partial H}{\partial N} = 0 \rightarrow \left[B_C + \pi\gamma\right] f_N = w; \tag{8}$$

$$\frac{\partial H}{\partial \gamma} = 0 \rightarrow -B_C g_\gamma + \eta f(N, R) = 0; \tag{9}$$

$$-\frac{\partial H}{\partial R} = \dot{\eta} - \eta\rho \rightarrow -B_C f_R - \eta\gamma f_R + b\eta = \dot{\eta} - \eta\rho; \tag{10}$$

$$\frac{\partial H}{\partial \eta} = \dot{R} \rightarrow \dot{R} = \gamma f(N, R) - bR. \tag{11}$$

Now the net price of wheat is $B_C + \eta\gamma$ where η is negative and the netting is done because more output implies an increment in current pollution produced. The shadow price η can be seen to equal $B_C g_\gamma / f(N, R)$ where $g_\gamma < 0$. Given this expression for η, we can solve for $\dot{\eta}$ and substitute for η and $\dot{\eta}$ in equations (8) and (10) to get three simultaneous differential equations in γ, N, and R. A steady state solution would have γ, N, and R at positive values, constant over time. We leave a detailed analysis of this model for another occasion since it is rather more complicated than its cousin above with no human-engineered abatement.

Economic Depreciation of Environmental Capital

Weitzman [1976] and others noted that the current Hamiltonian value in aggregate neoclassical growth theory is, given minor renormalization, an economy's NNP. Parts of NNP are net increases in the value of produced capital goods (net investment). But when neoclassical growth incorporates environmental capital, net "investment" includes the economic depreciation (value of declines) in these environmental capital goods. The steps of dynamic optimization yield market or scarcity values for all changes in capital stocks. Thus we end up with procedures for arriving at the correct measure of NNP, a measure which incorporates the current loss in value of environmental capital stocks due to increased pollution over the accounting period, say, one year.

We take up three variants of the approach – each turning on where pollution impinges on the economy and where abatement activities originate. First we consider no human abatement activity and negative pollution stock effects in the production function as in our simple Ricardian model. Then we consider produced abatement activity and again negative pollution stock effects in the production function. Finally, we introduce pollution effects into consumption activity or into the utility function. We add an "effect" at each stage. We observe 1) that there is a formal justification for netting pollution abatement costs from GNP [e.g., Peskin, 1976] in one variant, and 2) that there is a

netting out of rents on environmental capital in another variant. The netting out of exhaustible resource rents is introduced into Solow's [1986] (and here, our) framework and is discussed in Hartwick [1989] and Hartwick and Lindsey [1989]. See also Kemp and Long [1982].

NNP and the Economic Depreciation of Environmental Capital

We will treat the volume of pollution X, a stock concept, as an input into production. For given inputs K and L, more pollution will imply less output in $F(K, L, X)$.[4] In addition, the production of this composite output adds to pollution or results in a positive $\dot{X}$. Net pollution increments are $\dot{X} = -bX + \gamma F(K, L, X)$ where in the absence of production (a positive $F(\,)$), $\dot{X} = -bX$ or pollution "evaporates" at rate b by natural environmental stock regeneration. γ is a parameter linking produced output to increments in pollution. The aggregate planning problem has a single control variable C and two state variables, namely K and X, as in the maximized $\int_0^\infty e^{-\rho t} U(C)\,dt$, subject to $\dot{K} = F(K, L, X) - C$ and $\dot{X} = -bX + \gamma F(K, L, X)$, where ρ is the social discount rate and C is the aggregate consumption. $X(0)$, $K(0)$ and $L(0)$ are given exogenously. The current Hamiltonian value is:

$$H(t) = U(C) + \phi(t) \cdot [F(K, L, X) - C] + \psi(t) \cdot [-bX - \gamma F(K, L, X)]. \tag{12}$$

The canonical equations are:

$$\frac{\partial H}{\partial C} = 0 \text{ or } U_C = \phi(t); \tag{13}$$

$$\dot{\phi} = \rho\phi - \frac{\partial H}{\partial K} \text{ or } \dot{\phi} = \rho\phi - \phi F_K + \Psi\gamma F_K; \tag{14}$$

$$\dot{\Psi} = \rho\Psi - \frac{\partial H}{\partial X} \text{ or } \dot{\Psi} = \rho\Psi - \phi F_X + \Psi\gamma F_X + \Psi b; \tag{15}$$

$$\dot{K} = \frac{\partial H}{\partial \phi} \text{ or } \dot{K} = F(K, L, X) - C; \tag{16}$$

$$\dot{X} = \frac{\partial H}{\partial \Psi} \text{ or } \dot{X} = -bX + \gamma F(K, L, X). \tag{17}$$

To see that $H(t)$ is the NNP function, we represent $U(C) = C \cdot U_C$, observe $U_C = \phi$, and divide through by U_C to get

$$\frac{H(t)}{U_C} = C + \dot{K} + \frac{\Psi}{U_C}\dot{X}$$

or NNP inclusive of economic depreciation in environmental capital represented by $(\psi/U_C)\dot{X}$. Using the canonical equations further yields

$$\Psi/U_C = \left[\frac{\frac{-\dot{U}_C}{U_C} + \rho - F_K}{\gamma F_K}\right] = V.$$

Note that $V\dot{X}$ is a depreciation in terms of the pollution stock rather than the stock of environmental capital. This is a convenient way to model environmental resources.

In the absence of pollution, $V = 0$ because the numerator of V is zero. The numerator is in units of *rate of return* and F_K is the rate of return to capital in this polluted economy. Thus the numerator is a wedge in the rate of return and the denominator is *the* rate of return weighted by parameter γ. Thus the net rental, V, on a unit of pollution stock X is represented by a percentage wedge in the rate of return to produced capital K, namely F_K. Recall that co-state variables represent $\partial J(t)/\partial\alpha$ where α is a state variable and $J(t)$ is the value of the optimal program from t to the end of the program. Thus $\psi(t) = \partial J(t)/\partial X(t) < 0$ since a larger stock of X reduces the value of the program. $\psi(t)$ is in units of utility and $\psi(t)/U_C$ is the same concept, except in units of the composite produced good.

In the above formulation, pollution was only controlled indirectly via the output decision of producers. More output caused more pollution of stock size X and more pollution retarded production in the sense that the same amounts of K and L produce less output for higher levels of X. X was, formally speaking, a state variable and there was no control variable corresponding to or acting directly on X. With environmental capital our economic depreciation term involved rates of return rather than prices minus marginal cost. Suppose we reformulate the model by introducing a pollution abatement control. Might we not then observe economic depreciation in a price minus marginal cost form? Yes, we will. We introduce abatement costs $f(\gamma)$ as a debit from the produced composite output. A lower value of γ implies less new pollution per unit of composite output produced. Our current Hamiltonian value becomes:

$$H(t) = U(C) + \phi(t) \cdot [F(K, L, X) - C - f(\gamma)] + \psi(t) \cdot [-bX + \gamma F(K, L, X)] \quad (18)$$

where C and b are not control variables. From $\partial H/\partial C = 0$, we obtain $U_C = \phi$ and from $\partial H/\partial b = 0$, we obtain $f'\phi = F\psi$. Then $\frac{\Psi}{U_C} = \frac{f'}{F} < 0$ because $f' < 0$ and economic depreciation is $\frac{\Psi}{U_C}\dot{X} = \frac{f'\dot{X}}{F}$ where f' is the marginal cost

of decreasing the flow of produced pollution by investment in abatement "capital," a function of γ.

The generic economic depreciation term is $[\rho - mc]\dot{S}$ where $\dot{S}$ is the decline in the natural resource stock. In our case $\dot{X}$ (more pollution) represents the decline in environmental capital. We have no price here so $(\psi/U_C)\dot{X}$ should be interpreted as $[-mc]\dot{S}$. f' $(= df/d\gamma < 0)$ is a marginal cost and $\dot{X}/F$ is stock decline translated in "γ units." Then $f'\dot{X}/F$ is the measure of $\dot{X} > 0$ in extra units of composite output foregone.

This result provides a capital theoretic rationale for deducting current pollution control expenditures from GNP to arrive at an NNP figure (see for example Bartelmus, Stahmer, and van Tongeren [1989]). Note, however, that pollution control costs are expressed as an increment in pollution, $\dot{X}$, multiplied by the marginal cost of abating a unit of stock X. This is very different from using current resources expended in pollution control. This has been suggested by many people [e.g., Peskin, 1976]. Recall that Nordhaus and Tobin [1972, p. 49] netted out environmental degradation arising from pollution in an ad hoc fashion. If $\dot{X} < 0$ or pollution declines, then economic depreciation or $\frac{f'\dot{X}}{F} > 0$ becomes positive, representing an investment or capital appreciation, where the capital here is the stock of *clean* environmental capital.

Disutility of Pollution

A persuasive argument for not putting pollution in the utility function as in $U(C, X)$ is made by Usher [1981, pp. 130-34]. His argument can be labelled the sunshine problem. It does not make sense to put sunshine in $U(\,)$ or the love of God, and so on, as long as these stocks are *unchanging*. Similarly with the stock of pollution. But it does seem reasonable to assert that people are worse off if X increases or better off if X declines. This then is an argument for introducing changes in X into U if we consider that there are direct consumption or utility effects of pollution in addition to the deleterious effects of pollution on production.[5] Suppose then we revise our $U(C)$ above to incorporate changes in the pollution stock, $\dot{X} = -bX + \gamma F(K, L, X)$. Then our current Hamiltonian value is:

$$H(t) = U(C, \gamma F(K, L, X) - bX) + \phi(t) \cdot [F(K, L, X) - C - f(\gamma)] + \psi(t) \cdot [-bX + \gamma F(K, L, X)]. \tag{19}$$

Relations $\frac{\partial H}{\partial C} = 0$ and $\frac{\partial H}{\partial b} = 0$ yield $\frac{\Psi}{U_C} = \frac{-U_{\dot{X}}}{U_C} + \frac{f'}{F}$ where $-U_{\dot{X}}/U_C$

is the price of pollution increments, a positive number since $U_{\dot{X}} < 0$ for $\dot{X} > 0$ and $\frac{f'}{F} < 0$ as we noted above. Thus $\frac{\Psi}{U_C}$ is the price of extra pollution minus the marginal cost of extra pollution and this rent will be negative since $\psi(t) < 0$. That is, $\frac{-f'}{F} + \frac{U_{\dot{X}}}{U_C} > 0$ and economic depreciation is $\frac{\Psi(t)}{\phi(t)}\dot{X} = -\left[\frac{U_{\dot{X}}}{U_C} - \frac{f'}{F}\right]\dot{X} < 0$ for $\dot{X} > 0$, which should be added to GNP to obtain the lower correct NNP. Because X is a capital bad (as opposed to a capital good) our result is mirror symmetric to results for exhaustible resources. We have a sign change. Elsewhere economic depreciation was $[p\text{-}mc]\dot{\alpha}$ where α was a capital good, $\dot{\alpha}$ was negative, and $p\text{-}mc$ was a positive rent per unit of stock reduction. Immediately above, we have $[p\text{-}mc]\dot{X}$ where $\dot{X}$ is positive and $[p\text{-}mc]$ is negative since X (pollution stock) is a bad.

In the above analysis X and $\dot{X}$ entered directly into the large intertemporal optimization problem and as a result were priced at appropriate scarcity or shadow values. NNP was correctly valued given those shadow prices: F_X, $\frac{df}{d\gamma}$, and $U_{\dot{X}}/U_C$. In real-world economies there is generally no direct link between prices and pollution variables. Generally, the pollution stock will be excessive because appropriate charges for using airsheds and watersheds are not in place. To move from our abstract ideal valuations to actual evaluations is very difficult. When inputs are improperly priced, the wrong levels of outputs are produced at the wrong prices. Un- or under-priced environmental capital services are generally mispriced inputs. In actual problems, then, GNP has to be adjusted to take account of implicitly properly priced outputs and then, the appropriate netting out of depreciation of the environmental capital must be done. The trends in an adjusted NNP would provide a better indicator of how a nation's welfare is changing over time than, say, current NNP unadjusted for natural resource stock depreciation.

Appendix: Peskin on Accounting and Pollution

In Peskin [1976][6] the polluter uses the environment for his or her benefit and the value of this benefit is denoted EA_i for the ith polluting sector. The damage to consumers or pollutees (which may include polluters) is valued at R_i. Then $NEB_i = EA_i - R_i$ is the "net value of the environmental asset." (This terminology is misleading since Peskin distinguishes between the size of an asset, denoted A, and the residuals that asset can dissipate residuals $r(A)$. His analysis indicates that EA_i is the benefit or r to polluters and R_i is the disbenefit of r to pollutees.) Peskin argues that EA_i and R_i can be evaluated as totals or as marginal values weighted by quantities. Peskin's first approach is simply to add NEB_i summed over all i to GNP. The argument is that unpriced environmental flows should augment GNP and then the value of damage caused by those flows should be netted out of augmented GNP. This certainly parallels our conclusions derived in our capital theoretic framework. Peskin invokes an argument concerning optimal residual level r_i to analyse whether EA_i exceeds or falls short of R_i. In addition to the "optimal level" arguments, the sign will depend on whether total or marginal procedures are used. Recall that in our capital theoretic approach, we propose adding a value to observed GNP in order to account for the un- or under-priced services derived from environmental capital goods. We then advocated netting from this augmented GNP a value of the economic depreciation associated with a net increase in physical pollution levels in the air and watersheds. Note that our capital theoretic approach is based essentially on levels of residuals in the airsheds and watersheds (a stock concept) and on changes in those levels (stock adjustment or more or less residuals compared with current levels). We get explicit shadow prices on these magnitudes defined as equilibrium conditions. Peskin appeals to exogenously given marginal benefit and marginal damage schedules to carry out his valuations of r_i. These quantities appear to resemble annual crops in the sense that each year a certain series of r_i's are produced and they can vary from year to year, but these changes are not relevant. Valuation is based on these levels. Our approach is inherently dynamic in the sense that stocks of residuals and changes of stocks are essential quantities in the valuation process.

Notes

1 Usher [1981], Ward [1982], El-Serafy [1981], Eisner [1988] and Repetto [1989] discuss adjusting GNP in order to allow for using up of exhaustible resources.

2 Inherently dynamic models of production with pollution involved data from the 1960s. Some helpful contributions are Plourde [1972] and Forster [1973 and 1975]. Stochastic phenomena in a dynamic model are explored by Plourde and Yeung [1989].

3 Clark [1976, Section 6.5] provides a readable introduction to cycles as limiting processes in dynamical systems. Hartl [1987] shows formally that limit cycles cannot occur in models with just one state variable as we have set out above. The addition of produced capital to the model would yield a two-state model.

4 Martin [1986] has a detailed analysis of the complications arising from having a bad in the production function. Isoquants have unusual properties.

5 The Usher sunshine problem is in the tradition of valuing current well-being in flow (consumption) terms rather than in stock (wealth) terms. The stock of pollution is a wealth-like entity. If pollution (the stock) is steadily increasing over time, each concept will be reflected in $U(C, \cdot)$ declining for C constant. Usher's main justification for leaving wealth-like magnitudes such as sunshine out at all is because the approach leads to some non-intuitive results in measuring welfare over time [Usher, 1981, pp. 130-34]. But in cross-sectional or inter-country comparisons of welfare, stock magnitudes in $U(\ )$ make much sense, particularly stocks of pollutants in the air and water. It is not unfair to say that the science of inter-country welfare analysis has many aspects quite distinct from purely intertemporal welfare analysis for a single economy. The Weitzman [1976] – Solow [1986] framework is essentially one for intertemporal welfare analysis and we are in that framework in this contribution. Plourde and Forster, however, proceed to put pollution stock levels in the utility function.

6 Peskin [1981] contains a lengthy introduction where the environment is discussed as a form of capital which can be used up from excess pollution. The accounting analysis in the main part of the paper is the same as the accounting approach in Peskin [1976]. In Peskin [1986] there is explicit discussion of "depreciation in environmental assets" [see Eisner, 1988, p. 1674].

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